arXiv:nucl-th/9710016v1 6 Oct 1997

Electromagnetic and Strong Decays in a Collective Model of the Nucleon

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Abstract

We present an analysis of electromagnetic elastic form factors, helicity amplitudes and strong decay widths of non-strange baryon resonances, within a collective model of the nucleon. Flavor-breaking and stretching effects are considered. Deviations from the naive three-constituents description are pointed out.

Regularities in the observed mass spectra of baryons (*e.g.* linear Regge trajectories and parity doubling) suggest that a collective type of dynamics may play a role in the structure of baryons. It is of interest to test the scope and limitation of the collective scenario, contrast it with the single-particle type of dynamics present in quark potential models, and identify features in the experimental data which point at the need for additional degrees of freedom to supplement the naive effective description with only three constituents. In this contribution we present a particular collective model of baryons[1] and report on calculations of electromagnetic[2] and strong[3] couplings within this framework.

We consider a collective model in which nucleon and delta resonances are interpreted in terms of rotations and vibrations of a Y- shaped string configuration. The underlying shape is that of an oblate-top, with a (normalized) distribution of charges and magnetization

$$g(\beta) \;=\; \beta^2\, \mathrm{e}^{-\beta/a}/2a^3 \; . \tag{1}$$

Here β is a radial coordinate along the string and a is a scale parameter. The collective wave functions have the form $\left|\, ^{2S+1}\mathrm{dim}\{SU_f(3)\}_J\, [\mathrm{dim}\{SU_{sf}(6)\}, L^P]_{(v_1,v_2);K} \right\rangle$. The spin-flavor part has the usual $SU_{sf}(6)$ classification and determines the permutation symmetry of the state. The spatial part is characterized by the labels: $(v_1, v_2); K, L^P$, where (v_1, v_2) denotes the vibrations (stretching and bending) of the string; K denotes the projection of the rotational angular momentum L on the body-fixed symmetry-axis and P the parity. The spin S and L are coupled to total angular momentum J. In this notation the nucleon and the delta ground state wave functions are given by $\left|\, ^2 8_{1/2}\, [56, 0^+]_{(0,0);0} \right\rangle$ and $\left|\, ^4 10_{3/2}\, [56, 0^+]_{(0,0);0} \right\rangle$ respectively.

A collective model analysis[1,4] of the mass spectrum produced a fit for 3* and 4* non-strange resonances, of comparable quality to that of non-relativistic[5] and relativized[6] quark potential models. This shows that masses alone are not sufficient to distinguish between single-particle and collective forms of dynamics and one has to examine other observables which are more sensitive to the structure of wave-functions, such as electromagnetic and strong couplings. The electromagnetic (strong) transition operators are assumed to involve the absorption or emission of a photon (elementary meson) from a single constituent. The collective form factors are obtained by folding the matrix elements of these operators with the probability distribution of Eq. (1). In Ref.[1] these form factors are evaluated algebraically and closed expressions are derived in the limit of large model space. The ansatz of Eq. (1) for the probability distribution is made to obtain the dipole form for the elastic form factor. The same distribution is used to calculate inelastic form factors connecting other final states. All collective form factors are found[2] to drop as powers of Q^2. This property is well-known experimentally and is in contrast with harmonic oscillator based quark models in which all

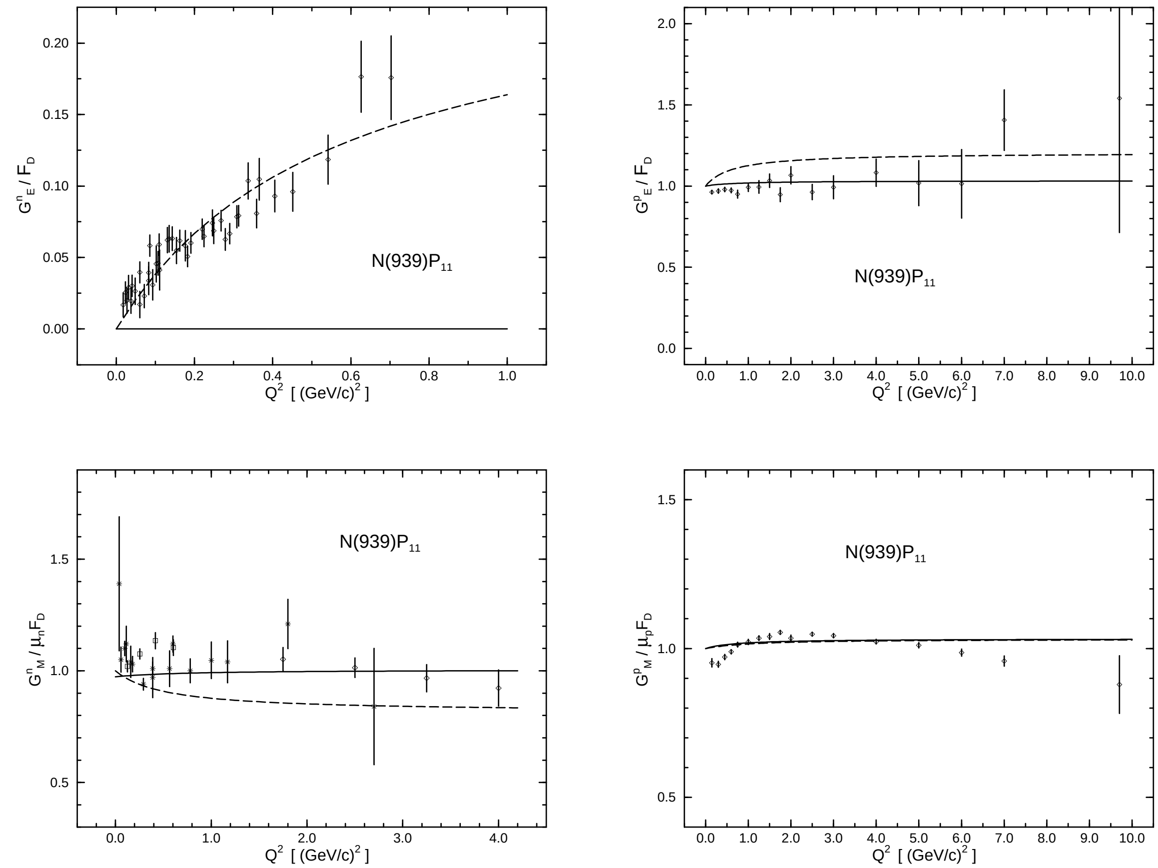

Fig. 1. Neutron and proton electric (G_E^n, G_E^p) and magnetic (G_M^n/μ_n, G_M^p/μ_p) form factors divided by $F_D = 1/(1+Q^2/0.71)^2$. Dashed (solid) lines correspond to a calculation with (without) flavor breaking.

form factors fall off exponentially. Within an effective model with three-constituents, in order to have a nonvanishing neutron electric form factor, as experimentally observed, one must break $SU_{sf}(6)$. We study this breaking by assuming a flavor-dependent distribution

$$\begin{aligned} g_u(\beta) &= \beta^2\, \mathrm{e}^{-\beta/a_u}/2a_u^3 \;, \\ g_d(\beta) &= \beta^2\, \mathrm{e}^{-\beta/a_d}/2a_d^3 \;. \end{aligned} \qquad (2)$$

The scale parameters a_u and a_d in Eq. (2) and the scale quark magnetic moments μ_u, μ_d are determined from a simultaneous fit to the proton and neutron charge radii, and to the proton and neutron electric and magnetic form factors. For the calculations in which the $SU_{sf}(6)$ symmetry is satisfied this procedure yields $a_u = a_d = a = 0.232$ fm and $\mu_u = \mu_d = \mu_p = 2.793$ μ_N ($= 0.127$ GeV^{-1}). When $SU_{sf}(6)$ symmetry is broken we find $a_u = 0.230$ fm, $a_d = 0.257$ fm, $\mu_u = 2.777\mu_N$ ($= 0.126$ GeV^{-1}) and $\mu_d = 2.915\mu_N$ ($= 0.133$ GeV^{-1}).

Fig. 1 shows the electric and magnetic form factors of the proton and the neutron. We see that while the breaking of spin-flavor symmetry can account for the non-zero value of G_E^n and gives a good description of the data, it worsens the fit to the proton electric and neutron magnetic form factors. There are also noticeable discrepancies at the low-Q^2 region $0 \le Q^2 \le 1$ (GeV/c)^2. This suggests that other contributions, such as coupling to the meson cloud[7]

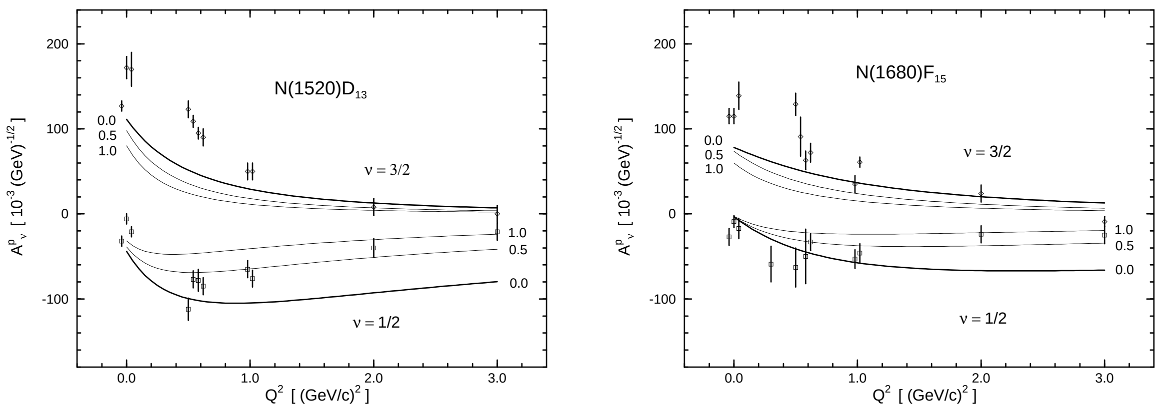

Fig. 2. Effect of hadron swelling for excitation of $N(1520)D_{13}$ and $N(1680)F_{15}$. The curves are labelled by the stretching parameter ξ of Eq. (3).

contribute in this range of Q^2. This conclusion (*i.e.* worsening the proton form factors) applies also to the other mechanisms of spin-flavor symmetry breaking, such as that induced by a hyperfine interaction[8].

The effect of spin-flavor breaking on helicity amplitudes A_ν ($\nu = 1/2, 3/2$) is rather small. Only in those cases in which the amplitude with $SU_{sf}(6)$ symmetry is zero, the effect is of some relevance. Such is the case with proton helicity amplitudes for the $^48_J[70, L^P]$ multiplet (*e.g.* the $L^P = 1^-$ resonances $N(1675)D_{15}$ and $N(1700)D_{13}$) and with neutron $\nu = 3/2$ amplitudes for the $^28_J[56, L^P]$ multiplet (*e.g.* the $L^P = 2^+$ resonance $N(1680)F_{15}$). In a string-like model of hadrons one expects[9] on the basis of QCD that strings will elongate (hadrons swell) as their energy increases. This effect can be included in the present analysis by making the scale parameters of the strings energy- dependent

$$a \;=\; a_0\Big(1 + \xi\,\frac{W - M}{M}\Big)\ . \tag{3}$$

Here M is the nucleon mass, W the resonance mass and ξ the stretchability parameter of the string. Fig. 2 shows that the effect of stretching on the helicity amplitudes for $N(1520)D_{13}$ and $N(1680)F_{15}$ is rather large (especially if one takes the value $\xi \approx 1$ which is suggested by QCD arguments[9] and the Regge behavior of nucleon resonances). The data show a clear indication that the form factors are dropping faster than expected on the basis of the dipole form.

In addition to electromagnetic couplings, strong decays of baryons provide an important, complementary, tool to study their structure. In the algebraic method the widths can be obtained in closed form which allows us to do a straightforward and systematic analysis of the experimental data. The calculated values depend on two parameters determined from a least square fit to the $N\pi$ partial widths (which are relatively well known) with the exclusion of the S_{11} resonances. These parameters are then used to calculate the decay channels ($N\pi$, $N\eta$, $\Delta\pi$, $\Delta\eta$) of *all* resonances. The calculation of decay widths of nucleon resonances into the $N\pi$ channel is found to be in fair agreement with experiment (see Table 1). The same holds for the $\Delta\pi$ channel[3]. These results are to a large extent a consequence of spin-flavor symmetry. There does not seem to be anything unusual in the decays into π and our analysis confirms the results of previous analyses[10,11]. Contrary to the decays into π, the decay widths into η have some unusual properties. The calculation gives systematically small values for these widths (see Table 1). This is due to a combination of phase space factors and the structure of the transition operator. In contrast, the 1996 PDG compilation[12] assigns a large η width to $N(1535)S_{11}$ and a small but non-zero η width to $N(1650)S_{11}$. The results of our analysis

Table 1. $N\pi$ and $N\eta$ decay widths of (3* and 4*) nucleon resonances in MeV. The experimental values are taken from[12].

State	Mass	Resonance	$\Gamma(N\pi)$		$\Gamma(N\eta)$	
			th	exp	th	exp
S_{11}	$N(1535)$	$^{2}8_{1/2}[70,1^{-}]_{(0,0);1}$	85	79 ± 38	0.1	74 ± 39
S_{11}	$N(1650)$	$^{4}8_{1/2}[70,1^{-}]_{(0,0);1}$	35	130 ± 27	8	11 ± 6
P_{13}	$N(1720)$	$^{2}8_{3/2}[56,2^{+}]_{(0,0);0}$	31	22 ± 11	0.2	
D_{13}	$N(1520)$	$^{2}8_{3/2}[70,1^{-}]_{(0,0);1}$	115	67 ± 9	0.6	
D_{13}	$N(1700)$	$^{4}8_{3/2}[70,1^{-}]_{(0,0);1}$	5	10 ± 7	4	
D_{15}	$N(1675)$	$^{4}8_{5/2}[70,1^{-}]_{(0,0);1}$	31	72 ± 12	17	
F_{15}	$N(1680)$	$^{2}8_{5/2}[56,2^{+}]_{(0,0);0}$	41	84 ± 9	0.5	
G_{17}	$N(2190)$	$^{2}8_{7/2}[70,3^{-}]_{(0,0);1}$	34	67 ± 27	11	
G_{19}	$N(2250)$	$^{4}8_{9/2}[70,3^{-}]_{(0,0);1}$	7	38 ± 21	9	
H_{19}	$N(2220)$	$^{2}8_{9/2}[56,4^{+}]_{(0,0);0}$	15	65 ± 28	0.7	
$I_{1,11}$	$N(2600)$	$^{2}8_{11/2}[70,5^{-}]_{(0,0);1}$	9	49 ± 20	3	

suggest that the large η width for the $N(1535)S_{11}$ is not due to a conventional q^3 state. One possible explanation is the presence of another state in the same mass region, *e.g.* a quasi-bound meson-baryon S wave resonance just below or above threshold, for example $N\eta$, $K\Sigma$ or $K\Lambda$[13]. Another possibility is an exotic configuration of four quarks and one antiquark ($q^4\bar{q}$).

The results reported in this article are based on work done in collaboration with F. Iachello (Yale). The work is supported in part by grant No. 94-00059 from the United States-Israel Binational Science Foundation (BSF), Jerusalem, Israel (A.L.) and by DGAPA-UNAM under project IN101997 (R.B.).

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